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Production of Heat-Resistant EP220 and EP929 Alloys by High-Temperature Treatment of Melt

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Abstract—Analysis of samples of EP220 and EP929 alloys in the liquid and solid state permits the determination of the parameters for high-temperature melt treatment in their production. On heating to specific temperatures, the structure of the liquid alloys moves closer to equilibrium. In the solidification of such melt, the cast metal formed is characterized by finer grain structure, greater dispersity of the dendrites, and greater density and microhardness of the matrix. Industrial adoption of high-temperature melt treatment will improve plasticity, increase the long-term strength, and boost the product yield. The proposed technology does not fully utilize the potential of the alloy structure obtained after high-temperature melt treatment. The effect may be amplified by more prolonged holding of the melt at 1650°C and by optimization of the vacuum-arc heating, deformation, and heat treatment, in the light of the structural changes in the experimental samples of solid metal.

Keywords: melt, physical properties, structural transformations, high-temperature melt treatment, solidification, cast metal, grain structure, mechanical properties

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The properties of heat-resistant alloys may be improved by high-temperature melt treatment during smelting or remelting [1–3]. This technology is of interest in the production of billet for subsequent treatment—in particular, in the manufacture of electrodes used in vacuum arc remelting.

As a rule, EP220 and EP929 alloys are produced within 1-t induction furnaces, in fused-magnesite crucibles. The maximum temperature is no more than 1600°C. The batch contains 40% plant waste and alloying composites. The metal is cast through a tundish in semicontinuous-casting machines. Each ingot is cut into five different parts, as electrodes for subsequent vacuum arc remelting. The quality is monitored in the final rod after appropriate processing and heat treatment.

EP220 and EP929 alloys are hard to deform and have been alloyed to the limit (Table 1); the degree of alloying exceeds 40% (Table 2, coefficient K_1). Therefore, their properties cannot be further improved by means of alloying, since that would lead to loss of deformability.

To determine the parameters of high-temperature melt treatment in the production of EP220 and EP929 alloys, samples are investigated in liquid and solid states.

The temperature dependence of the kinematic viscosity ν and electrical resistivity ρ is shown in Fig. 1. The results indicate that the molten batch is in disequilibrium and that there is scope for changing its structure by heating above the critical temperature t_{cr}.

Polytherms of the electrical resistance are particularly informative: they allow us to track the step-by-step changes in the melt structure. In the range from t_L to t_{an} (Fig. 1), ρ hardly increases, because the scattering of the conduction electrons at the thermal oscillation of the atoms increases with increase in the temperature (phonon scattering). To some extent, this range corresponds to thermal stability of the primary structure formed after batch melting: $\Delta t_{ts} = t_{an} - t_L$.

Evidently, Δt_{ts} will depend on various factors—in particular, the chemical composition. On the basis of Table 2 and Fig. 2, we see that the temperature range where the melt is thermally stable after batch melting rises with decrease in the alloying coefficient K_1 (the sum of all the alloying elements), in the coefficient K_2 (the sum of elements strengthening the solid solution), and in K_4 (the sum of carbide-forming elements). The alloys have similar values of K_3, which characterizes the formation of strengthening γ' phase, and therefore it has no influence on Δt_{ts}.

Between t_{an} and t_h, the structure of the melt changes rapidly, as it moves closer to equilibrium. Correspondingly, the atomic interaction becomes stronger, and the electrical resistance increases. Like t_{an}, the hysteresis temperature t_h increases with decrease in K_1, K_2, and

Table 1. Composition of heat-resistant alloys, wt %

Alloy	Ni	C	Cr	Co	Mo	W	Al	Ti	B	Fe
EP929	Balance	0.07	11.0	13.3	5.0	5.5	4.0	1.8	0.02	–
EP220	Balance	0.08	10.5	15.0	6.6	6.0	4.4	2.5	0.02	≤3.0

Table 2. Some characteristic temperatures and coefficients for molten EP220 and EP929 heat-resistant alloys

Alloy	t_{an}, °C	t_h, °C	t_{cr}, °C	Δt_{ts}	Δt_{ir}	K_1	K_2	K_3	K_4
EP929	1560	1660	1750	130	100	41	25	11	31.5
EP220	1470	1600	1650	60	130	48	31.5	12	38

K_3, but the temperature range of intense restructuring $\Delta t_{ir} = t_h - t_{an}$ shrinks.

In the interval Δt_{ir}, partial restoration of fragments of the primary structure is possible on cooling. Only heating above t_{cr} completes the formation of equilibrium structure. The critical temperature is determined by the coefficients K_1, K_2, and K_3: as they decrease, t_{cr} increases (Fig. 2). The importance of heating the melt to or above the critical temperature is confirmed by X-ray structural data.

The experimental data obtained indicate that, at 1500°C, the initial state of the melt is microheterogeneous. Therefore, the second intensity peak of the X-ray scattering, corresponding to the presence of fine structure, takes triplet form. The subpeaks observed are reflexes from different structural components of the melt. Holding the melt for 1 h at 1500°C does not change the structure. However, the melt structure changes on heating to 1700°C with subsequent cooling to 1500°C. The fine structure of the second maximum disappears; it becomes smooth. That corresponds to melt structure that is more uniform and closer to equilibrium.

The influence of the melt structure before solidification on the cast structure of the metal is investigated in laboratory melts produced in the following conditions:

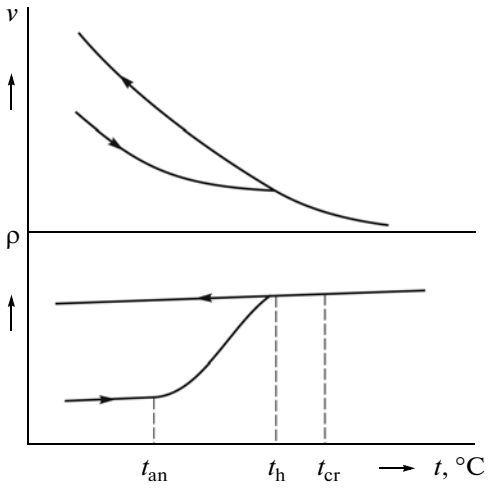

Fig. 1. Polytherms of the kinematic viscosity ν and electrical resistivity ρ and characteristic temperatures of heat-resistant alloys.

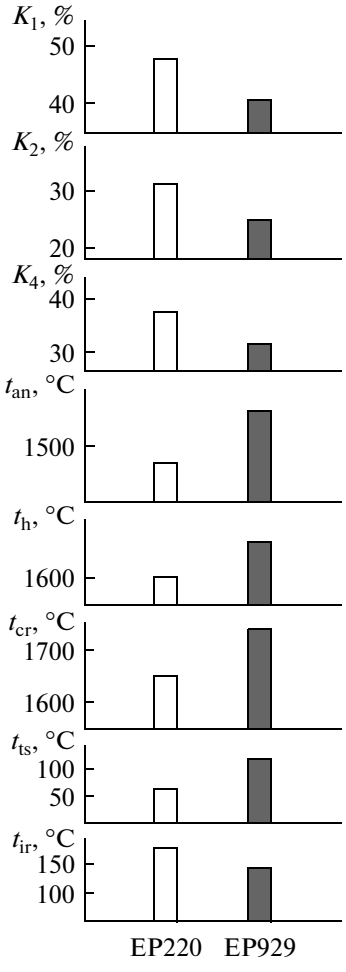

Fig. 2. Some characteristic temperatures and coefficients for molten EP220 and EP929 heat-resistant alloys.

Table 3. Conditions in model melts and microstructure of EP220 alloy samples

Characteristic	Melt					
	1	2	3	4	5	6
Specified initial temperature t_{sp}, °C	1600	1600	1660	1700	1750	1660
Holding time at t_{sp}, min	10	10	10	10	10	20
Wetting angle of crucible walls by melt, deg	115	111	81	103	98	87
Distance between second-order axes d_{II}, μm	77.7	75.6	61.0	66.3	58.5	59.6
Microhardness μ, MPa	4200	4260	4890	4470	4640	5280

(1) heating of alloy samples of grade composition to specific temperature t_{sp};

(2) holding at t_{sp} for 10 or 20 min;

(3) cooling to 1570°C at 10°C/min;

(4) holding at 1570°C for 10 min;

(5) cooling to 1250°C at 20°C/min;

(6) shutdown of the furnace.

Table 3 presents the conditions employed in the six cases considered; in all, 18 melts are studied.

Analysis of Table 3 indicates that the state of the melt is related to its wetting angle at the crucible walls: with increase in the wetting angle, the probability of surface defects in the ingot increases.

The macrostructure of the metal obtained with melt heating to 1660°C is preferable in terms of the wetting angle, the form of the shrinkage pores, and the position of the shrinkage defects.

If the melt is heated above t_{cr}, its microstructure changes. For example, in cases *1* and *2*, large randomly distributed dendrites are seen (Fig. 3a). With increase in the melt temperature to 1660°C in case *3* (Table 3), the dispersity of the dendrites increases, but the large-grain structure is retained (Fig. 3b). The difference between samples *2* and *6* is greatest. After heating the melt to 1660°C and holding for around 20 min, the dendrites in the cast metal become smaller but they are oriented in the direction of first- and second-order axes (Fig. 3c).

In case *6*, the microhardness is greatest (Table 3); it is increased by 23%. By analogy with other heat-resistant alloys, we may evidently conclude that the significant increase in matrix microhardness is due to increase in the quantity and dispersity of secondary γ'phase.

Thus, the results indicate intense transition of the melt structure to the equilibrium state on heating to the critical temperature. That significantly changes the structure and properties of the cast metal. The effect of high-temperature heating (~1660°C) is intensified on holding for up to 20 min. Further increase in temperature does not markedly affect the structure and properties of the cast metal.

On the basis of the experimental data, we may develop an experimental technology for melt production in an industrial induction furnace. After melting the usual batch materials, the melt is heated to 1650–1660°C, with holding for 10 min. Then the melt is cooled to 1550°C in 5–10 min. After adding ferroboron and nickel–magnesium alloy, the melt is heated before discharge to 1570–1590°C. The standard technology is used for all subsequent operations, including discharge, casting, treatment of the ingots, vacuum-arc remelting, deformational processing of the alloy, and heat treatment.

The quality of the metal is monitored in the cast state and after subsequent treatment. The size and position of the shrinkage defects permit trimming of the ingots by 30 cm. Surface defects (crust anomalies,

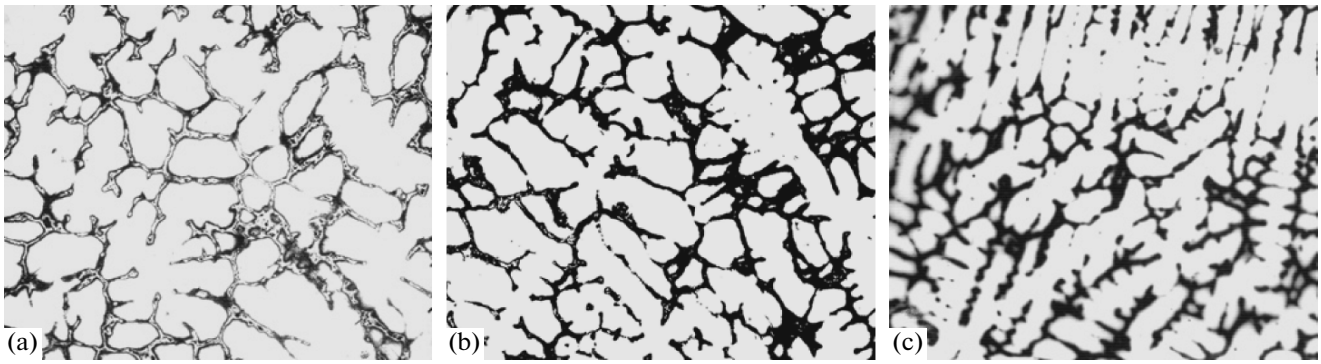

Fig. 3. Structure of model samples of EP220 alloy corresponding to cases *1* (a), *4* (b), and *6* (c) in Table 3.

Table 4. Properties of EP220 alloy

Samples	Mechanical properties at 950°C			Holding time at 900°C with a 280-MPa load, h	Microhardness of matrix, MPa	Density, kg/m^3
	σ_B, MPa	δ, %	φ, %			
Experimental	578	18.1	19	90	5450	8397
Industrial	573	13.6	10	76	5110	8364
Technical specifications	492	6	9	50	–	–

scratches, and bubbles) are very rare on the experimental samples and do not extend beyond 3 mm into the depth. The high quality of the ingot surface permits increase in the yield of cast metal for subsequent processing by 4%.

After rolling to bar, the experimental metal is in full compliance with the technical specifications. The strength σ_B, plasticity (δ and φ), time to failure at 900°C with a 280-MPa load, matrix microhardness, and density considerably exceed the mean values for industrial metal (Table 4). Note also the stability of the test results for metal from different experimental melts, in terms of all the characteristics considered, in contrast to industrial melts.

Thus, heating to specific temperatures results in more-equilibrium structure of liquid heat-resistant alloys. In the solidification of such melt, the cast metal formed is characterized by finer grain structure, greater dispersity of the dendrites, and greater density and microhardness of the matrix. Industrial adoption of high-temperature melt treatment will improve plasticity, increase the long-term strength, and boost the product yield.

Note that the proposed technology does not fully utilize the potential of the alloy structure obtained after high-temperature melt treatment. The effect may be amplified by more prolonged holding of the melt at 1650°C and by optimization of the vacuum-arc heating, deformation, and heat treatment, in the light of the structural changes in the experimental samples of solid metal.

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